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Original Research

Validity and reliability of a smartphone motion analysis app for lower limb kinematics during treadmill running

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A B S T R A C T

Objective: To investigate the validity and reliability of a smartphone application for selected lower-limb kinematics during treadmill running.
Design: Validity and reliability study.
Setting: Biomechanics laboratory.
Participants: Twenty healthy female runners.
Main outcome measure(s): Sagittal-plane hip, knee, and ankle angle and rearfoot eversion were assessed using the Coach's Eye Smartphone application and a 3D motion capture system. Paired *t*-test and intraclass correlation coefficients (ICC) established criterion validity of Coach's Eye; ICC determined test-retest and intrarater/interrater reliability. Standard error of measurement (SEM) and minimal detectable change (MDC) were also reported.
Results: Significant differences were found between Coach's Eye and 3D measurements for ankle angle at touchdown and knee angle at toe-off ($p < 0.05$). ICCs for validity of Coach's Eye were excellent for rearfoot eversion at touchdown (ICC = 0.79) and fair-to-good for the other kinematics (range 0.51–0.74), except for hip at touchdown, which was poor (ICC = 0.36). Test-retest (range 0.80–0.92), intrarater (range 0.95–0.99) and interrater (range 0.87–0.94) ICC results were excellent for all selected kinematics.
Conclusion: Coach's Eye can be used as a surrogate for 3D measures of knee and rearfoot in/eversion at touchdown, and hip, ankle, and rearfoot in/eversion at toe-off, but not for hip and ankle at touchdown or knee at toe-off. Reliable running kinematics were obtained using Coach's Eye, making it suitable for repeated measures.

1. Introduction

Running is one of the most popular sporting activities, but improper gait kinematics are associated with increased injury risk in runners (Verrelst R, Van Tiggelen D, De Ridder R, 2018). Kinematics such as hip flexion (Shen, Mao, Zhang, Sun, & Song, 2019), knee flexion (Mousavi et al., 2019) and ankle dorsiflexion (Pohl, Hamill, & Davis, 2009) have been reported as associated factors for running-related injuries. Rearfoot eversion is also of interest for clinical and research projects, yet debate is still ongoing regarding its association with running-related injuries (Ferber, Hreljac, & Kendall, 2009; Mousavi et al., 2019). Moreover, atypical knee and ankle flexion angles have been associated with reduced running economy (Moore, 2016). Measuring these kinematics is also important for research (Almeida, Davis, & Lopes, 2015) and movement performance while running (Estep, Morrison, Caswell, Ambegaonkar, & Cortes, 2018; Jafarnezhadgero, Alavi-Mehr, &

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Granacher, 2019). These kinematics are measured to assess joint stability (Delahunt et al., 2013) and stiffness (Sinclair, Shore, Taylor, & Atkins, 2015). Assessing these kinematic patterns during running is therefore of paramount interest for clinical practice and research as well as for improved running performance.

Because of their importance for running-related injuries, many studies investigated the aforementioned kinematic parameters during the stance phase of running, at touchdown and toe-off. For example, knee flexion at touchdown (Mousavi et al., 2019), ankle flexion at touchdown (Bramah, Preece, Gill, & Herrington, 2018) and toe-off (Goss & Gross, 2012), and hip flexion at toe-off (Tojima, Osada, & Torii, 2019) have been reported as contributing factors to running-related injuries. Milner, Hamill, and Davis (2007) reported that lower knee flexion at touchdown is a contributing factor to bone injuries due to the higher joint stiffness at touchdown and thus the increasing loading rate and shock absorption. These angles have been extensively assessed at touchdown and toe-off during running in biomechanical studies, with significant differences when comparing shoes (Hannigan & Pollard, 2020; Langley, Cramp, & Morrison, 2019), foot strike patterns (McCarthy, Fleming, Donne, & Blanksby, 2014), speeds (Fredericks et al., 2015), and overground versus treadmill (Firminger et al., 2018). Measurement of kinematics at touchdown and toe-off is additionally employed to identify the stance phase of the gait cycle.

Lower limb kinematic measurements are primarily taken using advanced three-dimensional (3D) motion analysis systems. However, despite 3D motion analysis systems being the gold standard in biomechanical research they are expensive and not always easily portable, which limits their use in clinical practice and on-field tasks. Moreover, the process for collecting 3D gait kinematic data is time-consuming and requires expertise to operate the system and analyze the data.

Use of smartphone applications (SPAs) to measure gait kinematics quantitatively has recently increased in both field and laboratory settings. Many individuals, including clinicians, researchers, coaches, and trainers, use SPAs to measure joint angles. Contrary to complex 3D motion analysis systems, an SPA is less expensive, portable, accessible, and easier to use. SPAs can also provide users with instant video feedback, which can enrich coaching quality and subsequently learning efficiency. Still, the lack of scientific studies to investigate their validity and reliability on measuring lower extremity joint angles during running is lacking.

The Coach's Eye application (TechSmith Corporation, USA, version 5, https://www.coachseye.com) is a two-dimensional (2D) motion analysis SPA that is being increasingly used in the gait analysis of various tasks in patients and healthy individuals. The Coach's Eye SPA has been downloaded more than one million times, according to the android app store (https://play.google.com/store/apps/details?id=com.techsmith.apps.coachseye.free). One distinguishing advantage of this SPA is its ability to provide frame-by-frame video playback with an unlimited frame rate, as compared to most SPAs, which have a maximum frame rate of 30 Hz (Mills, 2015). Previous studies report that Coach's Eye can provide valid and reliable kinematic measurements for wheelchair sitting posture, deep-squat test and elbow flexion (Alkhateeb, Forrester, Daher, Martin, & Alonazi, 2017; Krause et al., 2015; Mills, 2015). There is nonetheless a paucity of research investigating the validity and reliability of SPAs during treadmill running, including Coach's Eye.

Very few studies have compared 2D SPA measurements against gold-standard 3D motion capture systems during running. For example, a study reported that 2D measurements using Dartfish software were valid and reliable for frontal plane hip and knee angles during running (Maykut, Taylor-Haas, Paterno, DiCesare, & Ford, 2015). Additionally, only three studies have reported the validity of 2D motion video analysis for frontal plane kinematics during running (Atkins, James, Sizer, Jonely, & Brismée, 2014; Dingenen, Staes, et al., 2018; Maykut et al., 2015), and only three studies have investigated the reliability of 2D measures for lower limb kinematics (Damsted, Nielsen, & Larsen, 2015; Pipkin, Kotecki, Hetzel, & Heiderscheit, 2016; Reinking et al., 2018). Thus, evidence for validity of a 2D SPA for sagittal plane lower limb kinematic and rearfoot in/eversion measurements during running is lacking while 2D measurement of these kinematics comprises a considerable part of biomechanical researches as well as clinical practices for sport-related injuries.

The main objective of this study was therefore to assess the criterion validity of Coach's Eye for ankle, knee, and hip joint kinematics while running. The secondary aims were to evaluate test-retest, and intrarater/interrater reliability of Coach's Eye for kinematics while running.

2. Methods

2.1. Design

This study was designed to investigate the validity and reliability of the Coach's Eye SPA. To assess test-retest reliability, each runner ran twice with a five-minute interval. For intrarater reliability one rater assessed the kinematics twice with a five-day interval, and for interrater reliability two raters measured the selected kinematics using the SPA. To assess validity, measurements derived from the Coach's Eye SPA were compared to those derived from a 3D motion capture system.

2.2. Participants

According to a review about sample size determination for ICC measures between a new instrument and a gold standard (Bujang & Baharum, 2017), a minimum sample size of 18 was needed for an alpha value of 0.05 and a power of 80.0%. To this end, 20 healthy female recreational runners (age: 28 ± 4 years, height: 168 ± 5 cm, weight: 61 ± 6 kg) recruited by advertisement and social media postings volunteered to participate in this study. All subjects met the following inclusion criteria: (1) age between 18 and 40 years; (2) no self-reported history of major surgery or musculoskeletal deformity/injury in the lower and/or upper extremity in the past six months; (3) ran at least 10 km per week for six months prior to data collection; (4) experienced with treadmill running. Prior to testing, each participant read and signed an informed consent form. Ethical approval was given by the local Medical Ethics Committee (METc 2017.165) of University Medical Center Groningen.

2.3. Procedures

2.3.1. 3D gait analysis

Subjects were asked to wear running shorts, socks, and their own running shoes. A 3-camera, 3D motion capture system (Vicon Bonita, v2.2, Oxford, UK: 200 Hz) was used to collect 3D marker trajectory data. Similarly to previous studies (Phinyomark, Osis, Hettinga, & Ferber, 2015; Pohl, Lloyd, & Ferber, 2010), 16 reflective markers were placed on specific anatomical landmarks and five sets of marker clusters were placed on the bilateral shank and thigh as well as the pelvis (Fig. 1A). Three additional markers were attached directly to each of the subject's shoes; two heel markers were aligned vertically using a goniometer to define the vertical axis of the foot and a third marker was placed at the lateral side of the heel counter to complete a non-collinear marker set. Additional markers were placed on specific anatomical landmarks by the same experienced examiner, including the bilateral greater trochanter, lateral/medial knee joint line, and lateral/medial malleoli.

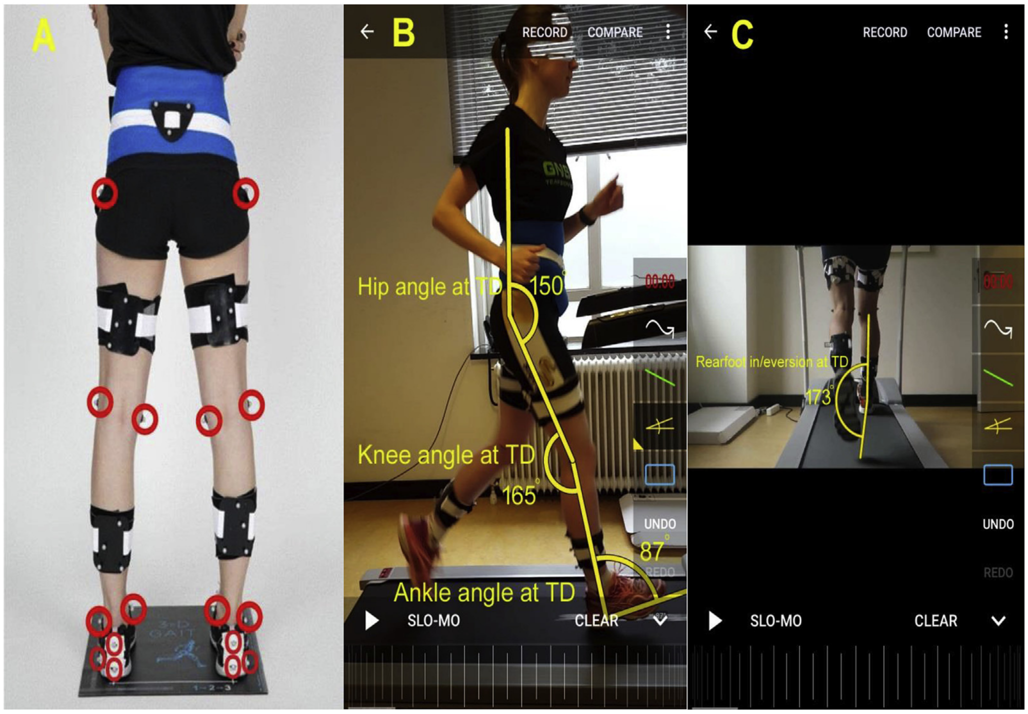

Fig. 1. Representative screenshots showing 3D marker placement and Coach's Eye measurement. A: 3D marker shell and marker placement; B: Coach's Eye measurements for sagittal plane hip, knee, and ankle angles at TD; C: rearfoot in/eversion at TD.

Each subject was allowed to do a 5-min warm-up and then asked to perform static and dynamic trials. According to the manufacturers' manual and guidelines, for the static trial subjects were asked to stand on the static calibration mat depicted in Fig. 1A so that two heel markers were aligned with the intersection of the white axes (forward and lateral axes) printed on the calibration mat. Subjects were then asked to align the midpoint between the first and fifth metatarsal heads with the forward-pointing axis of the calibration mat and arms crossed over the chest. Next, a 1-s trial was recorded. The dynamic trial was performed while running at the participant's self-selected speed on a treadmill (DTM900, Flow Fitness, Netherlands), and approximately 25 s of marker trajectory data were collected for analysis using custom software (Running Injury Clinic Inc., Calgary, Alberta, Canada) (Pohl et al., 2010). The mean of ten consecutive strides was calculated for each kinematic variable.

2.3.2. 3D data processing

Anatomical coordinate systems and technical coordinate systems were defined as explained in a previous study (Pohl et al., 2010). Marker coordinate data were collected at 200 Hz and marker trajectories were filtered using a 4th-order, zero-lag, low-pass Butterworth at 12 Hz. 3D joint kinematics were calculated following the general convention of calculating the 3D rigid body kinematics as distal segment relative to proximal segment. These calculations were consistent with the joint coordinate system as proposed by a previous study (Cole, Nigg, Ronsky, & Yeadon, 1993). Touchdown and toe-off were identified using a validated targeted machine learning approach that predicts the timing for foot strike (or initial contact) and toe-off, using only kinematics (Osis, Hettinga, & Ferber, 2016).

2.4. Video camera placement

Two video cameras (Canon, G16, 60 Hz, Japan) were used to capture the body movement of participants during treadmill running. The sagittal plane video was placed at a standardized 2 m from the right side of the treadmill at a height of 1 m so the subject's whole body was visible during recording. The frontal plane video was placed 1.5 m behind the treadmill at a height of 60 cm from the floor to record rearfoot motion. The optimal camera position was selected based on pilot testing.

2.4.1. Test procedure of smartphone application

The Coach's Eye application installed on a smartphone (Samsung Note5, android) was used for selected 2D kinematic measurements. Twenty-five seconds of each subject's running trial were simultaneously recorded with the video cameras as well as with the 3D motion capture system. All videos were imported into the smartphone to be analyzed using Coach's Eye. As a previous study concluded that at least 7 steps need to be analyzed in order to obtain a stable mean for 2D kinematic measures (Dingenen, Barton, Janssen, Benoit, & Malliaras, 2018), we decided to analyze 10 consecutive running steps using Coach's Eye for each variable. For the 2D analysis, touchdown was determined based on visual identification of the first frame showing heel contact with the treadmill (Pipkin et al., 2016; Souza, 2016) and toe-off was determined based on visual identification of the last frame showing toe contact with the treadmill (Souza, 2016). Table 1 describes the definition of kinematics measured within Coach's Eye and 3D motion capture system. To minimize 2D measurement error, all lines were drawn within Coach's Eye with the same S pen belonging to the smartphone. The right leg of all subjects was used to measure the sagittal plane kinematics of ankle, knee, and hip joints. Additionally, rearfoot in/eversion motion measurements of both legs were obtained for ten subjects (20 feet).

In order to be consistent with clinical measurements, the reported 2D hip, knee, and rearfoot angles were calculated by subtracting the Coach's Eye measurements from 180° (+flexion, -extension, + rearfoot inversion, - rearfoot eversion). The reported 2D ankle angles at touchdown and toe-off were calculated by

Table 1
Definition of measured variables.

Kinematics	Definition 2D	Definition 3D
Sagittal plane hip angle	The angle between the line drawn from the lateral femoral epicondyle marker to the greater trochanter marker and the line drawn from the greater trochanter marker to the front of the shoulder joint (acromion process, no marker) (Schurr et al., 2017).	The angle between femur and pelvis in the sagittal plane.
Sagittal plane knee angle	The angle between the line drawn from the greater trochanter marker to the lateral femoral epicondyle marker and the line drawn from the lateral femoral epicondyle marker to the lateral malleolus marker (Damsted et al., 2015).	The angle between shank and femur in the sagittal plane.
Sagittal plane ankle angle	The angle between the line drawn from the lateral femoral epicondyle marker to the lateral malleolus marker and the line drawn parallel to the lateral edge of the shoes (Pipkin et al., 2016).	The angle between foot and shank in the sagittal plane.
Rearfoot in/eversion	The angle between the line drawn from the middle of the lower leg crossing the middle of the Achilles tendon and the line joining the two posterior heel markers (Pipkin et al., 2016).	The angle between calcaneus and shank in the frontal plane.

subtracting the Coach's Eye measurements from 90° (+dorsiflexion, - plantar flexion). The same conventions were followed for 3D measurements. Fig. 1B and 1C represent how kinematic measures were obtained using Coach's Eye.

2.5. Data assessment

To evaluate the criterion validity of Coach's Eye, the measurements derived from Coach's Eye were compared to those derived from the 3D motion capture system. To evaluate test-retest reliability of Coach's Eye measures, all subjects were asked to run twice at the same running speed with a short 5-min interval between trials. The selected kinematic measures were then measured by the first rater (SHM) at touchdown and toe-off phases for both the first and second trials. To evaluate intrarater reliability, all angles already assessed for the first trial were reassessed by the same rater five days later using the same source data. To evaluate interrater reliability, all strides assessed by the first rater for each subject's first trial were reassessed by a second rater (FM). Each step from each video file used for assessment was specified using a time stamp and a stride number to ensure that the same steps were compared across and between raters. Raters were experienced researchers familiar with assessment of joint angles using 2D motion analysis systems (>6 years' experience). Raters were blinded to their fellow raters' measurements.

2.6. Statistical analysis

Data were analyzed using IBM SPSS version 23 (IBM Corp., Armonk, NY, USA), and Bland and Altman plots were utilized to visually inspect the 95% limits of agreement (LOA). To test criterion validity, paired t-tests were used to determine significant differences (if any) between Coach's Eye and 3D measures, followed by calculation of the intraclass correlation coefficient ($ICC_{2,k}$). $ICC_{2,k}$ was also used to determine test-retest and intrarater/interrater reliability for the kinematics measured using Coach's Eye. A significant difference was set at $p < 0.05$. According to the guidelines set by Fleiss and Paik, an ICC measurement of $r > 0.75$ was considered excellent reliability, $r = 0.40–0.75$ fair-to-good, and $r < 0.40$ poor (Fleiss, 1981). Since knowledge about reliability and absolute reliability index values such as minimal detectable change (MDC) and standard error of measurement (SEM) could help clinicians and researchers interpret data, both MDC and SEM were determined. SEM was calculated using the equation SD $\times \sqrt{(1\text{-ICC})}$ and MDC was calculated as SEM $\times$ 1.96 $\times \sqrt{2}$, at a 5% level of significance (95% confidence interval) (Donoghue & Stokes, 2009). The SEM and MDC were also normalized to the range (difference between minimum and maximum) of the separate joint angles of all participants.

3. Results

All participants in the current study exhibited a heel-strike running style. Results for criterion validity of Coach's Eye are shown in Table 2. The paired *t*-test showed significant differences between 3D and Coach's Eye measures for knee angle at toe-off (mean difference = −7, $p < 0.05$) and ankle angle at touchdown (mean difference = 4, $p < 0.05$). There were no significant differences for other kinematics. ICC values were excellent for rearfoot in/eversion at touchdown ($r = 0.79$) and fair-to-good for other kinematic measures ($r = 0.51$ to 0.74), except for hip angle at touchdown, which was poor ($r = 0.36$).

Test-retest reliability results of Coach's Eye for the selected joint angles are shown in Table 3. ICC results were excellent for all measurements ranging from $r = 0.8$ to 0.92. SEM results (percentage of the range of the angles) ranged from 0.81 to 1.90 (8–14%) and MDC (percentage of the range of the angles) ranged from 2.25 to 5.27 (22–38%).

Intrarater reliability results of Coach's Eye are shown in Table 4. ICC results for intrarater reliability were excellent for all measurements and ranged from $r = 0.95$ to 0.99. SEM results (percentage of the range of the angles) ranged from 0.43 to 1.10 (3–7%) and MDC (percentage of the range of the angles) ranged from 1.19 to 3.04 (8–19%).

Interrater reliability results of Coach's Eye are shown in Table 5. ICC results for interrater reliability were excellent for all measurements and ranged from $r = 0.87$ to 0.94. SEM results (percentage of the range of the angles) ranged from 0.68 to 1.60 (6–10%) and MDC (percentage of the range of the angles) ranged from 1.9 to 4.44 (17–27%).

Fig. 2 displays the 95% LOA for values obtained from 3D motion analysis compared to those obtained using Coach's Eye.

4. Discussion

The purpose of this study was to assess the criterion validity, test-retest and intrarater/interrater reliability of the Coach's Eye for hip, knee, and ankle joint kinematics while running.

4.1. Validity

Overall, compared to the gold-standard 3D motion capture system, Coach's Eye showed only 1–2 degrees of difference in kinematic measurements for the sagittal plane hip angles at touchdown and toe-off, sagittal plane knee angle at touchdown, sagittal plane ankle angle at toe-off, and rearfoot angles at touchdown and toe-off. However, measures of ankle angle at touchdown and knee angle at toe-off were not as accurate and the Bland and Altman plots show a substantial bias ranging from 4 to 20° for the 95% LOA when comparing the results of the 3D system with Coach's Eye (Fig. 1).

Table 2
Criterion validity results of Coach's Eye against 3D motion analysis system for kinematics measured.

Angle (degree)	3D mean (SD)	Coach's Eye mean (SD)	Mean difference 3D-Coach's Eye (SD)	Mean absolute difference 3D-Coach's Eye (SD)	ICC*	95% CI
Hip at TD†	35 (3)	33 (3)	2 (4)	3 (2)	0.36	−0.09-0.68
Hip at TO†	3 (6)	3 (5)	0 (5)	3 (3)	0.51	0.10–0.77
Knee at TD†	18 (5)	16 (3)	2 (3)	3 (2)	0.68	0.34–0.86
Knee at TO†	18 (6)	25 (7)	−7‡ (5)	7 (5)	0.61	0.24–0.83
Ankle at TD†	9 (3)	5 (3)	4‡ (2)	4 (2)	0.59	0.22–0.82
Ankle at TO†	12 (5)	13 (4)	−1 (4)	3 (2)	0.68	0.35–0.86
Rearfoot in/eversion at TD	8 (3)	7 (3)	1 (1)	2 (1)	0.79	0.55–0.91
Rearfoot in/eversion at TO	7 (3)	8 (4)	−1 (2)	2 (2)	0.74	0.44–0.89

ICC Intraclass correlation coefficient, * ICC >0.75 excellent, 0.40 ≤ ICC ≤ 0.75 fair-to-good, ICC <0.40 poor SD standard deviation, CI confidence interval, † sagittal plane, TD touchdown, TO toe-off, ‡ significant difference between Coach's Eye and 3D measures ($p < 0.05$).

Table 3
Test-retest reliability results of Coach's Eye for kinematics measured.

Angle (degree)	Measurements, mean (SD)		ICC[a]	95% CI	SEM	SEM%	MDC	MDC%
Hip at TD[b]	A. 33 (3)	B. 33 (2)	0.81	0.64–0.93	0.99	12.68	2.74	35.16
Hip at TO[b]	A. 3 (5)	B. 3 (4)	0.87	0.71–0.95	1.54	9.11	4.27	25.25
Knee at TD[b]	A. 16 (3)	B. 17 (3)	0.81	0.58–0.92	1.44	11.33	3.99	31.41
Knee at TO[b]	A. 25 (7)	B. 24 (6)	0.91	0.78–0.96	1.90	10.22	4.97	28.32
Ankle at TD[b]	A. 5 (3)	B. 5 (3)	0.8	0.56–0.92	1.20	13.96	3.33	38.48
Ankle at TO[b]	A. 13 (4)	B. 12 (3)	0.90	0.76–0.96	1.13	9.49	3.13	26.29
Rearfoot in/eversion at TD	A. 7 (3)	B. 8 (3)	0.92	0.70–0.97	0.81	8.53	2.25	23.65
Rearfoot in/eversion at TO	A. 8 (3)	B. 8 (3)	0.90	0.76–0.96	1.11	7.78	3.06	21.58

ICC Intraclass correlation coefficient.
[a] ICC >0.75 excellent, 0.40 ≤ ICC ≤ 0.75 fair-to-good, ICC <0.40 poor SD standard deviation, CI confidence interval, MDC minimal detectable change, SEM standard error of measurement, SEM% normalized SEM to the range of angles, MDC% normalized MDC to the range of angles.
[b] Sagittal plane, TD touchdown, TO toe-off, A. first measurement, B. second measurement.

Table 4
Intrarater reliability results of Coach's Eye for kinematics measured.

Angle (degree)	Assessments mean (SD)	ICC[a]	95% CI	SEM	SEM%	MDC	MDC%
Hip at TD[b]	1.34 (3) 2.33 (3)	0.98	0.94–0.99	0.44	4.71	1.22	13.08
Hip at TO[b]	1.3 (5) 2.3 (4)	0.98	0.95–0.99	0.64	4.17	1.78	11.56
Knee at TD[b]	1.16 (3) 2.16 (4)	0.99	0.96–0.99	0.43	2.94	1.19	8.14
Knee at TO[b]	1.25 (7) 2.24 (7)	0.97	0.93–0.99	1.1	5.32	3.04	14.76
Ankle at TD[b]	1.5 (3) 2.5 (2)	0.95	0.88–0.98	0.55	7.01	1.53	19.42
Ankle at TO[b]	1.13 (4) 2.13 (3)	0.97	0.93–0.99	0.61	5.16	1.69	14.29
Rearfoot in/eversion at TD	1.7 (3) 2.7 (3)	0.97	0.94–0.99	0.45	4.92	1.26	13.65
Rearfoot in/eversion at TO	1.8 (4) 2.8 (3)	0.95	0.87–0.98	0.76	5.49	2.12	15.23

ICC Intraclass correlation coefficient.
[a] ICC >0.75 excellent, 0.40 ≤ ICC ≤ 0.75 fair-to-good, ICC <0.40 poor SD standard deviation, CI confidence interval.
[b] Sagittal plane, TD touchdown, TO toe-off, 1. first assessment, 2. second assessment, SEM% normalized SEM to the range of angles, MDC% normalized MDC to the range of angles.

Results also show a substantial bias for the knee angle at toe-off, which could be attributed to the different methods employed to detect the toe-off event in Coach's Eye and the 3D motion analysis system. Additionally, analyzing Coach's Eye data using a 60 Hz frame rate captured by a video camera versus 200Hz for the 3D motion analysis system may reduce the accuracy of determining the exact touchdown and toe-off events for Coach's Eye. A previous study also reported differences in measurements for common gait events using cameras with different frame rate (Ferber, Sheerin, Kendall, & Kendall, 2009).

A possible reason for the wide range of bias in the current study could be that the touchdown and toe-off events were determined visually, whereas a validated algorithm was used to determine these events with the 3D software package. The angles obtained from the 3D analysis system might therefore be different from those measured by Coach's Eye at the specified time point. Another possible consideration is that the foot progression angle (the angle between the longitudinal axes of the foot and of the treadmill – the global coordinate system) at touchdown, either a toe-in or a toe-out position, can lead to perspective error since the foot position will be out of the sagittal plane; this may have led to the underestimated ankle angle measured using Coach's Eye compared to the 3D system. This discrepancy was not accounted for in determining the ankle angle at toe-off, and it is therefore possible that participants

Table 5
Interrater reliability results of Coach's Eye for kinematics measured.

Angle (degree)	Raters mean (SD)	ICC[a]	95% CI	SEM	SEM%	MDC	MDC%
Hip at TD[b]	A. 33 (3) B. 33 (3)	0.91	0.78–0.96	0.82	9.61	2.27	26.65
Hip at TO[b]	A. 3 (5) B. 4 (4)	0.94	0.85–0.97	1.14	7.20	3.17	19.95
Knee at TD[b]	A. 16 (3) B. 17 (4)	0.93	0.84–0.97	0.97	6.05	2.7	16.77
Knee at TO[b]	A. 25 (7) B. 24 (5)	0.93	0.83–0.97	1.60	8.66	4.44	23.99
Ankle at TD[b]	A. 5 (3) B. 4 (2)	0.91	0.80–0.97	0.68	9.05	1.9	25.08
Ankle at TO[b]	A. 13 (4) B. 14 (3)	0.92	0.80–0.97	1.01	8.91	2.79	24.70
Rearfoot in/eversion at TD	A. 7 (3) B. 8 (2)	0.92	0.82–0.97	0.73	7.81	2.01	21.66
Rearfoot in/eversion at TO	A. 8 (4) B. 8 (3)	0.87	0.70–0.95	1.23	8.42	3.41	23.32

ICC Intraclass correlation coefficient.
[a] ICC >0.75 excellent, 0.40 ≤ ICC ≤ 0.75 fair-to-good, ICC <0.40 poor SD standard deviation, CI confidence interval.
[b] Sagittal plane, TD touchdown, TO toe-off, A. first rater, B. second rater, SEM% normalized SEM to the range of angles, MDC% normalized MDC to the range of angles.

might have obtained a more neutral foot progression angle near toe-off as the foot exhibits a "heel whip" in response to torsional forces (Souza et al., 2015).

Low ICC values were found when comparing Coach's Eye to 3D measures of hip angle at touchdown. 2D assessment of the hip flexion/extension angle may differ from 3D measures, as the 3D hip flexion/extension angle is calculated from the movement between the markers placed on the pelvis and femur, whereas the 2D measure in the current study involves the angle determined by a line drawn from the lateral femoral epicondyle to the greater trochanter and another line drawn from the greater trochanter to the front of shoulder joint. Nevertheless, a previous study comparing 2D and 3D measurements of sagittal plane hip angle during a single-leg squat reported a strong correlation between the two measurements (Schurr, Marshall, Resch, & Saliba, 2017). In fact, these authors applied the same method of 2D measurement (the angle between the lines joining the acromion process, greater trochanter, and lateral femoral epicondyle to each other) to assess hip angle as used in the current study. It is therefore possible that excess upper limb movement during running plays more of a role in measurement error than during a single-leg squat. We recommend that for 2D measures of running, the line joining the greater trochanter to the acromion process is not an appropriate alternative to represent sagittal plane pelvic movement and thus reduces the validity of 2D versus 3D measurements.

No significant differences were found between Coach's Eye and 3D rearfoot motion assessments for either touchdown or toe-off in the current study. These findings are consistent with those of Cornwall and McPoil (1995), but their results were reported during walking. Although we found no significant differences between Coach's Eye and 3D assessments for measuring rearfoot in/eversion, some issues should be considered when assessing rearfoot in/eversion using Coach's Eye. The rapid external rotation of the tibia and the abnormal foot progression angle potentially occurring at toe-off should be considered (Souza et al., 2015), and the nature of the 2D analysis might prevent accurate measurement of rearfoot motion, especially at toe-off when using a camera frequency of 60Hz or less (Ferber, Sheerin, et al., 2009). Another issue is that in both touchdown and toe-off the heel is never perpendicular to the camera, which can affect the 2D measurement of rearfoot eversion. Additionally, when measuring rearfoot motion at toe-off there is the possibility of an overlap of both vertical rearfoot markers, which would reduce measurement accuracy.

4.2. Reliability

The secondary aims of the current study were to evaluate the test-retest and intrarater/interrater reliability of SPA for kinematic measures while running. The results of this study demonstrate excellent test-retest reliability for all joint kinematic measures. These results are consistent with a recent study that also demonstrated excellent test-retest reliability for hip, knee, and ankle kinematic measurements during a deep-squat test using Coach's Eye (Krause et al., 2015). Another study also reported moderate-to-excellent test-retest reliability using 2D video analysis while running for measures of knee flexion (ICC = 0.87) and ankle dorsiflexion (ICC = 0.90) in the right leg, and knee flexion (ICC = 0.89) and ankle dorsiflexion (ICC = 0.73) in the left leg (Dingenen, Barton, et al., 2018).

The results also show excellent intrarater/interrater reliability in all kinematics measured using Coach's Eye. These results are in agreement with previous literature that has also reported high intrarater/interrater reliability for 2D video assessment of lower limb kinematics (Damsted et al., 2015; Pipkin et al., 2016; Rabin, Einstein, & Kozol, 2018). Ankle and knee sagittal plane kinematics at midstance and initial contact using a 2D video analysis have been reported to exhibit moderate-to-excellent agreement for interrater and intrarater reliability measures (Pipkin et al., 2016). Similar reliability measures for hip and knee sagittal plane angles at initial contact during running were reported for 2D video measures and 95% LOAs ranging from 3 to 8° within-day and 9–14° between-day (Damsted et al., 2015).

SEM and MDC measures for test-retest and intrarater/interrater reliability of these kinematics were <2 and < 5, respectively. Reinking et al. (2018) reported SEMs for intrarater reliability among raters with various degrees of experience assessing 2D analysis of knee flexion and rearfoot eversion at touchdown during running: SEMs were 11% of the mean of knee flexion at touchdown and 61% of the mean of rearfoot eversion at touchdown (averaged across all raters). These SEMs are much larger than those for intrarater reliability that we found for these angles (3% of the mean knee at touchdown and 6% of the mean rearfoot eversion at touchdown). Dingenen, Barton, et al. (2018) reported MDCs, expressed as the percentage of range, for test-retest reliability of 2D measurement of knee flexion and ankle dorsiflexion at midstance during running: MDCs were 19.5% for knee flexion and 23% for ankle dorsiflexion. These are smaller than the MDCs we found for both knee angle (31-

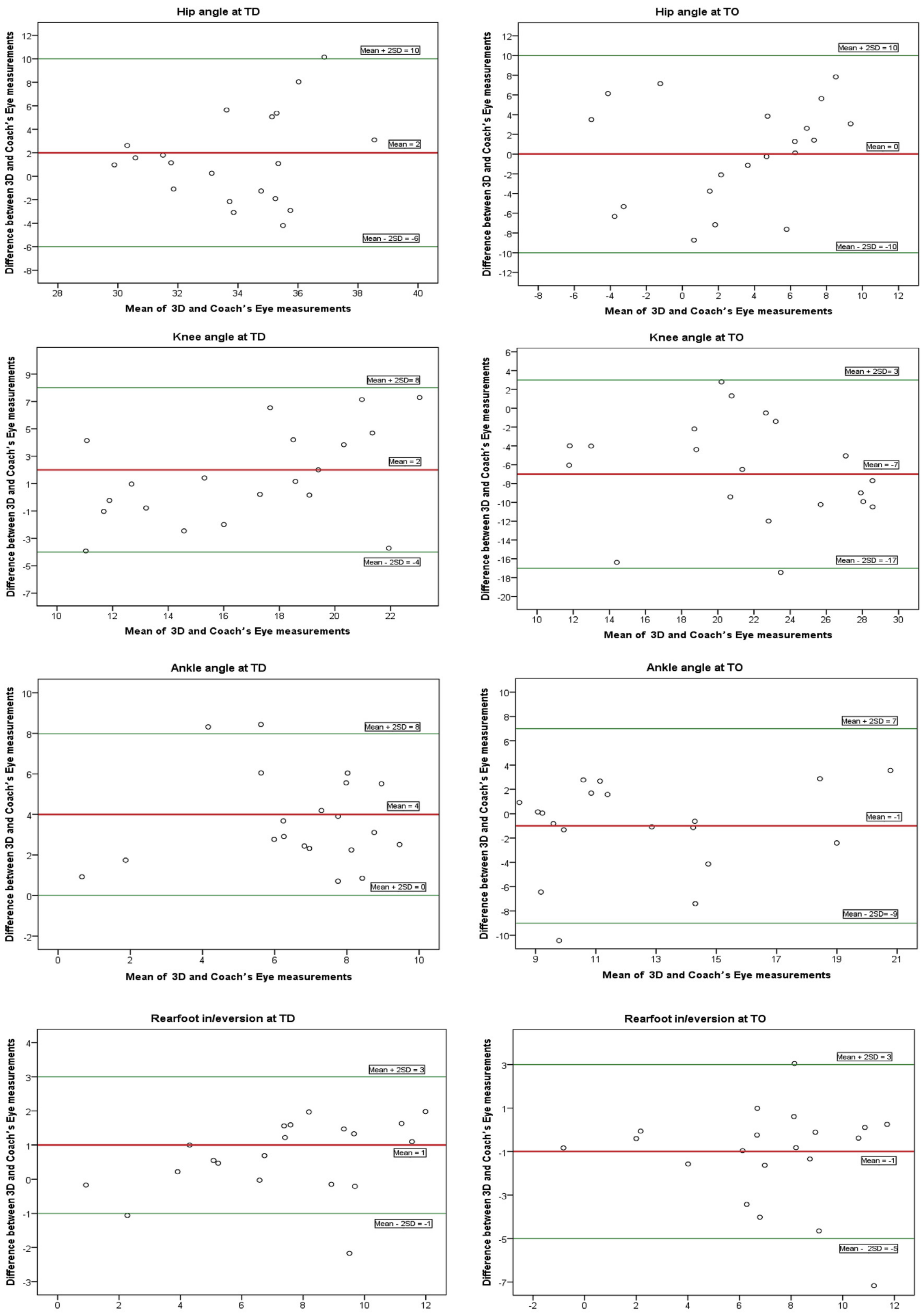

Fig. 2. Bland and Altman limits for the 3D and Coach's Eye measurements. All measurements are in degrees. The red horizontal line represents the mean difference, the green lines the 95% limits of agreement. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

28%) and ankle angle (38-26%). This can be due to the reasons given for the detection of touchdown and toe-off events in our study versus midstance in the Dingenen study.

Given that no study has so far investigated the validity and reliability of an SPA or 2D video analysis system for measuring rearfoot in/eversion during running, the current findings create a basis for using Coach's Eye to assess potential atypical rearfoot in/eversion.

The kinematics investigated in our study are considered as factors associated with running-related injuries (Mousavi et al., 2019; Pohl et al., 2009; Shen et al., 2019; Verrelst R, Van Tiggelen D, De Ridder R, 2018). Measurement of these kinematics is also of interest for research (Langley et al., 2019). Hence clinicians, researchers, and coaches may use Coach's Eye to reliably record and assess sagittal plane lower-limb joint kinematics and rearfoot in/eversion at the clinic or on the field.

4.3. Practical implications

This study provides practical implications for using Coach's Eye in the assessment of running gait kinematics. While height of camera from running surface should be taken into account in order to obtain reliable data, using a stylus is also recommended for drawing lines within Coach's Eye, as drawing lines by hand may produce inaccurate and unreliable data. Using cameras with a high frame rate (>60Hz) can help minimize measurement error of the selected gait parameters during running such as touchdown, midstance and toe-off. It is more efficient to record videos directly using Coach's Eye installed on a smartphone, yet keeping in mind that the quality of the video recorded by Coach's Eye (e.g. sampling rate) is dependent on the quality of the smartphone's camera.

4.4. Limitations

Some limitations should be considered when interpreting the results of the current study. First, given that these results are limited to healthy female runners, caution should be taken when generalizing them to male and/or injured runners or other sporting conditions. Second, all subjects in the current study were rearfoot strikers, which may affect generalization of results to non-rearfoot stickers. Third, to assess test-retest reliability runners ran twice with a five-minute interval in-between, while most studies considered waiting a few days between test and retest. In addition, the markers were not removed between test and retest. These shortcomings may affect the comparability of our results to other studies. Fourth, in order to provide results that are as accurate as possible, all lines were drawn using an S-pen, which suggests that the results cannot be generalized to those drawn by hand or using other applications. Although 2D and 3D systems collected data simultaneously, there could be an offset in the data collected and subsequently used for analysis. Having the subjects perform a specific task (e.g. a single gait cycle with increased knee flexion) or using an electronic sync signal could be used for time synchronization between systems.

4.5. Recommendations for future research

Future research may consider alternative methods that are less sensitive to the trunk transverse plane rotation to make the upper line/vector (e.g. a line from the greater trochanter either perpendicular or parallel to the surface or parallel to the trunk or to the ear lobule, or a marker on the lateral aspect of the neck) to assess hip flexion/extension during running using Coach's Eye or any other similar SPAs. These suggested alternative methods may enhance the validity of results derived from SPAs for measuring hip angle. Future research may also consider comparing the kinematic results derived from Coach's Eye with other similar SPAs measuring kinematics. This could identify the advantages and disadvantages as well as the shortcomings of SPAs tailored to measure kinematic angles. Measurement of peak angles and angles in midstance using SPAs while running is also recommended for future studies, as assessing kinematics during these gait events is also of interest to clinical practice and research. The unique intrinsic characteristics of the cameras used to capture motion in the current study, placed with a fixed geometric setup and a fixed lens focus on all subjects, might affect generalization of results to other camera models or brands. Hence future research may consider the effect of camera positioning (height, distance, angle) as well as the effect of intrinsic camera parameters such as optical center, focal length, framing rate, optical and sensor resolution, and motion blur when capturing motion during running.

5. Conclusion

The current study reveals that Coach's Eye provides reliable measures of sagittal plane hip, knee, and ankle, and rearfoot in/eversion kinematic angles with excellent test-retest and intrarater/interrater reliability. Significant differences were found for ankle angle at touchdown and knee angle at toe-off between Coach's Eye and 3D measures. ICC for the validity of Coach's Eye was poor for hip at touchdown (0.36), excellent for rearfoot at touchdown (0.79) and fair to good for other variables measured (0.51–0.74). Coach's Eye can therefore be used as a surrogate for 3D measures of knee and rearfoot in/eversion at touchdown, and hip, ankle, and rearfoot eversion at toe-off, but not for hip and ankle at touchdown or knee at toe-off. Alternative methods for measuring 2D sagittal plane hip angle such as a line from the lateral epicondyle to the greater trochanter and a line from the greater trochanter either perpendicular or parallel to the surface or parallel to the trunk or to the ear lobule or lateral aspect of the neck may be explored by future studies to improve the validity of 2D sagittal plane hip angle measurement during running.

Ethical approval

Ethical approval was given by the local Medical Ethics Committee (METc 2017.165) of University Medical Center Groningen. Each participant read and signed an informed consent form.

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None declared.

Declaration of competing interest

This study did not target a product promotion of either the Samsung smartphone or camera or the Coach's Eye app used in the current study. None of these companies were involved in any part of the research.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ptsp.2020.02.003.

References

Alkhateeb, A. M., Forrester, B. J., Daher, N. S., Martin, B. D., & Alonazi, A. A. (2017). Validity and reliability of wheelchair sitting posture measures using Coach's Eye in abled subjects. *Assistive Technology, 29*(4), 210–216. https://doi.org/10.1080/

10400435.2016.1220994.
Almeida, M. O., Davis, I. S., & Lopes, A. D. (2015). Biomechanical differences of foot-strike patterns during running: A systematic review with meta-analysis. *Journal of Orthopaedic & Sports Physical Therapy, 45*(10), 738–755. https://doi.org/10.2519/jospt.2015.6019.
Atkins, L. T., James, C. R., Sizer, P. S., Jonely, H., & Brismée, J.-M. (2014). Reliability and concurrent criterion validity of a novel technique for analyzing hip kinematics during running. *Physiotherapy Theory and Practice, 30*(3), 210–217. https://doi.org/10.3109/09593985.2013.830349.
Bramah, C., Preece, S. J., Gill, N., & Herrington, L. (2018). Is there a pathological gait associated with common soft tissue running injuries? *The American Journal of Sports Medicine, 46*(12), 3023–3031. https://doi.org/10.1177/0363546518793657.
Bujang, M. A., & Baharum, N. (2017). A simplified guide to determination of sample size requirements for estimating the value of intraclass correlation coefficient: A review. *Archives of Orofacial Sciences, 12*(1), 1–11.
Cole, G. K., Nigg, B. M., Ronsky, J. L., & Yeadon, M. R. (1993). Application of the joint coordinate system to three-dimensional joint attitude and movement representation: A standardization proposal. *Journal of Biomechanical Engineering, 115*(4A), 344–349.
Cornwall, M. W., & McPoil, T. G. (1995). Comparison of 2-dimensional and 3-dimensional rearfoot motion during walking. *Clinical Biomechanics, 10*(1), 36–40. https://doi.org/10.1016/0268-0033(95)90435-C.
Damsted, C., Nielsen, R. O., & Larsen, L. H. (2015). Reliability of video-based quantification of the knee- and hip angle at foot strike during running. *International Journal of Sports Physical Therapy, 10*(2), 147–154.
Delahunt, E., Chawke, M., Kelleher, J., Murphy, K., Prendiville, A., Sweeny, L., et al. (2013). Lower limb kinematics and dynamic postural stability in anterior cruciate ligament-reconstructed female athletes. *Journal of Athletic Training, 48*(2), 172–185. https://doi.org/10.4085/1062-6050-48.2.05.
Dingenen, B., Barton, C., Janssen, T., Benoit, A., & Malliaras, P. (2018). Test-retest reliability of two-dimensional video analysis during running. *Physical Therapy in Sport, 33*, 40–47. https://doi.org/10.1016/j.ptsp.2018.06.009.
Dingenen, B., Staes, F. F., Santermans, L., Steurs, L., Eerdekens, M., Geentjens, J., et al. (2018). Are two-dimensional measured frontal plane angles related to three-dimensional measured kinematic profiles during running? *Physical Therapy in Sport, 29*, 84–92. https://doi.org/10.1016/J.PTSP.2017.02.001.
Donoghue, D., & Stokes, E. (2009). How much change is true change? The minimum detectable change of the berg balance scale in elderly people. *Journal of Rehabilitation Medicine, 41*(5), 343–346. https://doi.org/10.2340/16501977-0337.
Estep, A., Morrison, S., Caswell, S., Ambegaonkar, J., & Cortes, N. (2018). Differences in pattern of variability for lower extremity kinematics between walking and running. *Gait & Posture, 60*, 111–115. https://doi.org/10.1016/j.gaitpost.2017.11.018.
Ferber, R., Hreljac, A., & Kendall, K. D. (2009a). Suspected mechanisms in the cause of overuse running injuries: A clinical review. *Sport Health, 1*(3), 242–246. https://doi.org/10.1177/1941738109334272.
Ferber, R., Sheerin, K., Kendall, M. K. D., & Kendall, M. K. (2009b). Measurement error of biomechanical gait parameters between a 100Hz and 30Hz camera. *International Sportmed Journal, 10*(3), 152–162.
Firminger, C. R., Vernillo, G., Savoldelli, A., Stefanyshyn, D. J., Millet, G. Y., & Edwards, W. B. (2018). Joint kinematics and ground reaction forces in overground versus treadmill graded running. *Gait & Posture, 69*, 109–113. https://doi.org/10.1016/j.gaitpost.2018.04.042.
Fleiss, J. (1981). The measurement of interrater agreement. In *Statistical methods for rates and proportions* (pp. 212–236).
Fredericks, W., Swank, S., Teisberg, M., Hampton, B., Ridpath, L., & Hanna, J. B. (2015). Lower extremity biomechanical relationships with different speeds in traditional, minimalist, and barefoot footwear. *Journal of Sports Science and Medicine, 14*(2), 276–283.
Goss, D. L., & Gross, M. T. (2012). A review of mechanics and injury trends among various running styles. *U.S. Army Medical Department Journal*, 62–71.
Hannigan, J. J., & Pollard, C. D. (2020). Differences in running biomechanics between a maximal, traditional, and minimal running shoe. *Journal of Science and Medicine in Sport, 23*(1), 15–19. https://doi.org/10.1016/j.jsams.2019.08.008.
Jafarnezhadgero, A., Alavi-Mehr, S. M., & Granacher, U. (2019). Effects of anti-pronation shoes on lower limb kinematics and kinetics in female runners with pronated feet: The role of physical fatigue. *PloS One, 14*(5), e0216818. https://doi.org/10.1371/journal.pone.0216818.
Krause, D. A., Boyd, M. S., Hager, A. N., Smoyer, E. C., Thompson, A. T., & Hollman, J. H. (2015). Reliability and accuracy of a goniometer mobile device application for video measurement of the functional movement screen deep squat test. *International Journal of Sports Physical Therapy, 10*(1), 37–44.
Langley, B., Cramp, M., & Morrison, S. C. (2019). The influence of motion control, neutral, and cushioned running shoes on lower limb kinematics. *Journal of Applied Biomechanics, 35*(3), 216–222. https://doi.org/10.1123/jab.2018-0374.
Maykut, J. N., Taylor-Haas, J. A., Paterno, M. V., DiCesare, C. A., & Ford, K. R. (2015). Concurrent validity and reliability of 2D kinematic analysis of frontal plane motion during running. *The International Journal of Sports Physical Therapy, 10*(2), 136–146.
McCarthy, C., Fleming, N., Donne, B., & Blanksby, B. (2014). 12 Weeks of simulated barefoot running changes foot-strike patterns in female runners. *International Journal of Sports Medicine, 35*(5), 443–450. https://doi.org/10.1055/s-0033-1353215.
Mills, K. (2015). Motion analysis in the clinic: There's an app for that. *Journal of Physiotherapy, 61*(1), 49–50. https://doi.org/10.1016/J.JPHYS.2014.11.014.
Milner, C. E., Hamill, J., & Davis, I. (2007). Are knee mechanics during early stance related to tibial stress fracture in runners? *Clinical Biomechanics, 22*(6), 697–703. https://doi.org/10.1016/j.clinbiomech.2007.03.003.
Moore, I. S. (2016). Is there an economical running technique? A review of modifiable biomechanical factors affecting running economy. *Sports Medicine, 46*, 793–807. https://doi.org/10.1007/s40279-016-0474-4.
Mousavi, S. H., Hijmans, J. M., Rajabi, R., Diercks, R., Zwerver, J., & van der Worp, H. (2019, March 1). *Kinematic risk factors for lower limb tendinopathy in distance runners: A systematic review and meta-analysis*. Gait and Posture. Elsevier B.V. https://doi.org/10.1016/j.gaitpost.2019.01.011.
Osis, S. T., Hettinga, B. A., & Ferber, R. (2016). Predicting ground contact events for a continuum of gait types: An application of targeted machine learning using principal component analysis. *Gait & Posture, 46*, 86–90. https://doi.org/10.1016/j.gaitpost.2016.02.021.
Phinyomark, A., Osis, S., Hettinga, B. A., & Ferber, R. (2015). Kinematic gait patterns in healthy runners: A hierarchical cluster analysis. *Journal of Biomechanics, 48*(14), 3897–3904. https://doi.org/10.1016/j.jbiomech.2015.09.025.
Pipkin, A., Kotecki, K., Hetzel, S., & Heiderscheit, B. (2016). Reliability of a qualitative video analysis for running. *Journal of Orthopaedic & Sports Physical Therapy, 46*(7), 556–561. https://doi.org/10.2519/jospt.2016.6280.
Pohl, M. B., Hamill, J., & Davis, I. S. (2009). Biomechanical and anatomic factors associated with a history of plantar fasciitis in female runners. *Clinical Journal of Sport Medicine, 19*(5), 372–376. https://doi.org/10.1097/JSM.0b013e3181b8c270.
Pohl, M. B., Lloyd, C., & Ferber, R. (2010). Can the reliability of three-dimensional running kinematics be improved using functional joint methodology? *Gait & Posture, 32*(4), 559–563. https://doi.org/10.1016/j.gaitpost.2010.07.020.
Rabin, A., Einstein, O., & Kozol, Z. (2018). Agreement between visual assessment and 2-dimensional analysis during jump landing among healthy female athletes. *Journal of Athletic Training, 53*(4), 386–394. https://doi.org/10.4085/1062-6050-237-16.
Reinking, M. F., Dugan, L., Ripple, N., Schleper, K., Scholz, H., Spadino, J., et al. (2018). Reliability of two-dimensional video-based running gait analysis. *International Journal of Sports Physical Therapy, 13*(3), 453–461.
Schurr, S. A., Marshall, A. N., Resch, J. E., & Saliba, S. A. (2017). Two-dimensional video analysis is comparable to 3D motion in lower extremity movement assessment. *International Journal of Sports Physical Therapy, 12*(2), 163–172.
Shen, P., Mao, D., Zhang, C., Sun, W., & Song, Q. (2019). Effects of running biomechanics on the occurrence of iliotibial band syndrome in male runners during an eight-week running programme—a prospective study. *Sports Biomechanics, 11*, 1–11. https://doi.org/10.1080/14763141.2019.1584235.
Sinclair, J., Shore, H. F., Taylor, P. J., & Atkins, S. (2015). Sex differences in limb and joint stiffness in recreational runners. *Human Movement, 16*(3), 137–141. https://doi.org/10.1515/humo-2015-0039.
Souza, R. B. (2016). An evidence-based videotaped running biomechanics analysis. *Physical Medicine and Rehabilitation Clinics of North America, 27*(1), 217–236. https://doi.org/10.1016/j.pmr.2015.08.006.
Souza, R. B., Hatamiya, N., Martin, C., Aramaki, A., Martinelli, B., Wong, J., et al. (2015). Medial and lateral heel whips: Prevalence and characteristics in recreational runners. *PM&R, 7*(8), 823–830. https://doi.org/10.1016/j.pmrj.2015.02.016.
Tojima, M., Osada, A., & Torii, S. (2019). Changes in hip and spine movement with increasing running speed. *Journal of Physical Therapy Science, 31*(8), 661–665. https://doi.org/10.1589/jpts.31.661.
Verrelst, R., Van Tiggelen, D., De Ridder, R., & Witvrouw, E. (2018). Kinematic chain-related risk factors in the development of lower extremity injuries in women: A prospective study. *Scandinavian Journal of Medicine & Science in Sports, 28*(2), 696–703. https://doi.org/10.1111/sms.12944.